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## Original software publication

# A Stochastic Anaerobic Digestion Economic Assessment Tool (SADEAT)

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## ABSTRACT

Deterministic approaches to analysing the economic feasibility of anaerobic digestion (AD) projects can lead to non-robust results. Stochastic approaches are inherently robust because they simultaneously explore multiple stochastic AD variables based on their probability distributions. However, few research papers on AD economics have used a stochastic approach in part due to the unavailability of tools for doing so. This paper presents a freely available stochastic AD economic assessment tool (SADEAT) to help private firms, farmers and scientists interested in robustly assessing the economic feasibility of AD projects and/or policymakers seeking to explore policy options for the industry.

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## Code metadata

Current code version	v1.0.2
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Legal Code License	GNU General Public License
Code versioning system used	git
Software code language	MATLAB
Compilation requirement	Windows operating system and MATLAB R2015a or later
If available link to documentation	<a href="https://github.com/AbdulSalam2016/SADEAT-Stochastic-Combined-Heat-and-Power-Anaerobic-Digestion-Economic-Assessment-Tool/releases/tag/1.0.2">https://github.com/AbdulSalam2016/SADEAT-Stochastic-Combined-Heat-and-Power-Anaerobic-Digestion-Economic-Assessment-Tool/releases/tag/1.0.2</a>

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Legal Software License	GNU General Public License
Computing platform / Operating System	Microsoft Windows
Installation requirements & dependencies	2.00GB RAM, 1.50 GHz frequency
If available Link to user manual—if formally published include a reference to the publication in the reference list	<a href="https://github.com/AbdulSalam2016/SADEAT-Stochastic-Combined-Heat-and-Power-Anaerobic-Digestion-Economic-Assessment-Tool/releases/tag/1.0.2">https://github.com/AbdulSalam2016/SADEAT-Stochastic-Combined-Heat-and-Power-Anaerobic-Digestion-Economic-Assessment-Tool/releases/tag/1.0.2</a>
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## 1. Introduction

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Anaerobic digestion (AD) is a process by which micro-organisms break down biodegradable material in the absence of

oxygen, leading to the production of biogas and digestate. AD technologies convert the methane in biogas into electricity and heat. In general there is increasing public support for AD projects in many countries hence necessitating governmental interventions for the industry. For example, the UK and its devolved parliaments have introduced a number of policies designed to incentivise investments in AD projects. Among these are policies aimed at enhancing AD economics (e.g. feed-in-tariffs, renewable heat incentives, renewable obligation certificates, levy exemption certificates, etc.); and policies aimed at channelling the potential of biodegradable waste for low carbon renewable energy generation (e.g. landfill ban for biodegradable waste, ban on macerators, legislation requiring separate food waste collections, etc.). These policies further the UK's goal towards a low carbon economy and its commitment to renewable energy targets. More importantly, the policies together have created opportunities for the AD industry in the UK which has experienced substantial growth over the past decade, from under 20 AD plants in 2006 to over 400 in 2017.

Accrued or displaced revenues from sale or on-site use of electricity and heat; and the sale or on-site use of digestate as well as the costs of setting up and running an AD project are the basis of an economic feasibility analysis of the project. There are mixed results in the literature regarding the economic feasibility of AD projects. Most studies have found AD projects to be economically unviable. Example studies include [1–4] and [5]. These studies adopt a deterministic methodological approach. However, the realisation of many AD project variables are inherently stochastic, a fact that is by definition not accommodated in deterministic approaches to AD economics. For example, the methane content in biogas can fluctuate in the range 55–80 [6]. In deterministic analyses, a single value in this range is typically assumed as is the case in [7] who assume a value of 60%. In a stochastic approach however, multiple simulated cases of an AD project can be calibrated to realise different values in this range, based on a probability distribution of the realisation of values in the range. In their stochastic approach for example, [8] assume the methane content in biogas to be triangularly distributed with minimum value of 55%, modal value of 60% and maximum value of 80%. The advantage of the stochastic approach is that a distribution of decision support indicators can be drawn from the multiple simulated cases of a single AD project. This gives a robust determination of the expected outcome of the project. Indeed [8] argue that use of a stochastic methodological approach ‘provides more robust results relative to previous work’ which use deterministic approaches.

To the best of the author's knowledge, all of the freely available AD decision support tools adopt a deterministic methodological approach, and are typically simple spreadsheets only. An example is the tool offered by [9] and [10]. As argued above however, a deterministic approach is non-robust, an inherent limitation that is by definition addressed with a stochastic methodological approach. With the growing demand for sustainable renewable energy, robust and freely accessible stochastic economic assessment tools are needed by private firms, farmers, scientists and policy makers who seek to consider investment opportunities in AD projects and/or explore policy options for the industry. This paper presents a stochastic AD economic assessment tool (SADEAT). SADEAT is developed with MATLAB software and utilises an advanced user friendly interface. SADEAT is freely available to download<sup>1</sup> and is compatible for installation on computers operating on a Windows platform. SADEAT has been successfully used for modelling AD economics in a recent peer reviewed publication (see [11]).

The remainder of this paper proceeds as follows: In Section 2, we mention the economic feasibility decision support indicators underlying SADEAT and mathematically demonstrate how one of the indicators is calculated in SADEAT. In Section 3, we briefly describe the SADEAT interface and inbuilt error controls. In Section 4, we introduce an example AD project and present the results outputted by SADEAT on the economic feasibility of that project. For robustness checks, we compare the SADEAT result with that of an existing deterministic tool offered by [10]. Section 5 concludes the paper.

## 2. Models underlying the software

SADEAT calculates 4 indicators of the economic feasibility of an AD project. These are (1) net present value (NPV); (2) modified internal rate of return (MIRR); (3) breakeven electricity price; and (4) breakeven heat price. SADEAT comes with a detailed user guide showing how the 4 indicators are calculated. Here, we example how one of the indicators (i.e. NPV) is calculated. Consider that a user wishes to simulate  $N$  stochastic cases of an AD project which has a project horizon of  $T$  years. Let  $i$  represent the set of the  $N$  stochastically simulated cases of this project and  $t$  represent the set of  $T$  years of the project lifetime. Also let *elecPriceGenFIT* and *elecPriceExport* represent the initial year feed-in-tariff (FIT) for AD electricity and the initial year export price of electricity respectively. Now let *heatPriceRHI* represent the initial year renewable heat incentive (RHI) tariff for heat generated by AD and *heatPriceExport* represent the initial year export price of heat. The above prices are the relevant prices for AD generated electricity and heat in the UK but can be interpreted generically and applied for other contexts. Given these prices, the NPV of each of  $N$  simulated cases of an AD project can be calculated as follows;

*solve NPV* ( $i$ ) =  $-totalCapitalCost$  ( $i$ )

$$NPV(i) + \sum_{t=0}^{T-1} (cashFlow(i, t) / (1 + discountRate)^{t-1}) \quad (1)$$

where

$$cashFlow(i, t) = postTaxProfit(i, t) + machineryDepreciationCost(i, t) + buildingDepreciationCost(i, t) \quad (2)$$

$$postTaxProfit(i, t) = preTaxProfit(i, t) - tax(i, t) \quad (3)$$

$$tax(i, t) = taxRate \times preTaxProfit(i, t) \forall preTaxProfit(i, t) > 0 \quad (4)$$

$$preTaxProfit(i, t) = annualRevenue(i, t) - overheadCost(i, t) - loanRepaymentCost(i, t) - machineryDepreciationCost(i, t) - buildingDepreciationCost(i, t) \quad (5)$$

$$annualRevenues(i, t) = electricityRevenue(i, t) + heatRevenue(i, t) \quad (6)$$

$$electricityRevenue(i, t) = ((elecPriceGenFIT + elecPriceExport) / 100) \times (1 + inflationRate)^{t-1} \times annualElectricityGeneration(i, t) \quad (7)$$

$$heatRevenue(i, t) = ((heatPriceRHI + heatPriceExport) / 100) \times (1 + inflationRate)^{t-1} \times annualHeatGeneration(i, t) \quad (8)$$

$i \in \{1, \dots, N\}$  simulated cases,  $t \in \{0, 1, \dots, T - 1\}$  years

<sup>1</sup> See <https://github.com/AbdulSalam2016/SADEAT-Stochastic-Combined-Heat-and-Power-Anaerobic-Digestion-Economic-Assessment-Tool/releases>. A web version of SADEAT is available at [www.energybusinessseconomics.com](http://www.energybusinessseconomics.com).

The variable names in model (1)–(8) above are suggestive and self-explanatory. Readers may refer to the associated SADEAT user guide for a detailed description of these variables. Note in model (1)–(8) that SADEAT allows user input of initial year electricity and heat prices only. These initial year prices are then annually inflated over the project lifetime based on a user specified inflation rate (see Eqs. (7) and (8); divisions by 100 in these equations convert p/kWh to £/kWh). Note also that in capital budgeting analyses, depreciation costs are added to the post-tax cashflow because depreciation costs do not represent cash outflows (i.e. see Eq. (2)). They do however determine the project tax bill hence are first subtracted from the pre-tax profit (i.e. see Eq. (5)). The feedstock and bio-physical properties of each simulated case is stochastically simulated hence revenues for each simulated case would be different, leading to  $N$  different NPVs. The distribution of these NPVs provides robust understanding of the expected NPV of the simulated AD project. Readers may refer to the associated SADEAT user guide for a detailed description of how the remaining 3 indicators of AD economic feasibility are calculated.

### 3. Software interface and error controls

#### 3.1. The interface

SADEAT interface has 3 key parts as shown in Fig. 1. These are (1) the 'Menu Bar', (2) the 'Tab Selection Panel' and (3) the 'Input and Result Tabs'.

The 'menu bar' is on top of the interface and has 4 components. These are 'File', 'Run', 'Export results' and 'Help'. These allow the user to exit SADEAT (by selecting 'File' → 'Exit'), run SADEAT (by selecting 'Run' → 'NPV', 'MIRR' or the breakeven prices), export the software results to excel (by selecting 'Export results' → 'Export data') or access the associated software user guide (by selecting 'Help' → 'Open user guide'). The 'Input and result tabs' allow the user to input the AD project variables and also view the results of SADEAT calculations. The user may also achieve this goal by using the 'Tab selection panel'. There are 10 tabs overall, of which 1 is the face of SADEAT, 6 are user input tabs and 3 are results tabs. The tabs are summarised below. Please see the full user guide for details.

##### 3.1.1. 'Welcome' tab

This is the face of SADEAT and contains the contact details and affiliations of the author, as shown in Fig. 1.

##### 3.1.2. Cases/lifetime/seed

This is a user input tab. The tab allows the user to specify (1) the number of cases of an AD project the user wishes to simulate, (2) the lifetime of the project and (3) the seed number that controls stochastic behaviour of project parameters. Users may specify between 10 and 10,000 cases to simulate. The larger the number of cases simulated, the longer it takes for SADEAT to complete calculations. The minimum and maximum lifetimes of an AD project are also restricted to 5 and 20 years respectively. The maximum restriction of 20 years is imposed because Feed-in-tariff (FIT) and renewable heat incentive (RHI) payments are typically awarded for up to a maximum of 20 years only. The seed number controls the stochastic behaviour of SADEAT. Results are reproducible if the seed number is unchanged. For a different set of results to be simulated, users have to change the seed number which then re-sets SADEAT stochastic behaviour. The seed number can be any positive integer.

##### 3.1.3. Costs

This is a user input tab with 3 panels namely (1) 'Building and infrastructure capital costs, £', (2) 'Machinery capital costs, £' and (3) 'Overhead costs, £' (see Fig. 2). The first and second panels allow the user to input the capital costs for buildings/infrastructure and machinery. Users must note that the entry 'Grant assistance' is a capital income, not a capital cost; and so it is subtracted from the total capital costs of building/infrastructure and/or machinery. When inputting building/infrastructure and machinery capital costs, users must include replacement costs. The third panel allows the user to input overhead costs. The resulting total overhead cost is that of the initial project period only. The total overhead cost for subsequent project periods increases at the rate of inflation set by the user in tab 'Prices and Rates'. Note that building, machinery and overhead costs are not stochastic parameters hence all simulated cases of an AD project assume the same values for these costs.

##### 3.1.4. Costs summary

This is a user input tab. The tab allows the user to input further information related to the cost of an AD project. These include the duration for depreciating the building and machinery capital costs, the percentage of total capital cost that is funded with debt as well as the duration for repaying the debt. The tab also summarises information regarding the cost of the project. These include textual as well as graphical summaries which are automatically updated if the user changes information about project costs.

##### 3.1.5. Prices and rates

This is a user input tab. The tab allows the user to input various prices and money/finance related rates. These include FIT for electricity, export price of electricity, RHI for heat, and the export price of heat. The tab also allows the user to input rates including the interest rate for debt, the inflation rate for costs and prices, the discount rate for discounting cashflows and the tax rate, the MIRR finance rate and the MIRR reinvestment rate. All rates are expressed in 0–100 percent. Note that prices and rates are not stochastic parameters hence all simulated cases of an AD project assume the same values for prices and rates.

##### 3.1.6. Feedstock

This is a user input tab (see Fig. 3). The tab allows the user to input information about the types of feedstock of an AD project, the feedstock amounts and the feedstock biogas yields. Feedstock amount and biogas yields are stochastic parameters and their realisations for each simulated case of an AD project depends on their user entered ranges and user selected distributions. The user is presented with an option to select either of (1) a uniform or (2) a triangular distribution. When triangular distribution is selected, the user inputs the minimum, modal and maximum values for the parameters. When uniform distribution is selected, the modal entries are disabled.

##### 3.1.7. Energy conversion

This is a user input tab. The tab allows the user to input information related to an AD unit's conversion of biogas from feedstock to electricity and heat energy. Most of the parameters regard the efficiency of an AD unit. The parameters in this tab are stochastic and the user has the option to choose either a uniform or triangular distribution for the parameters.

##### 3.1.8. Simulated data

This is a result tab. The tab allows the user a detailed tabular view of the income statement of each simulated case for each year. Annual revenues, costs, cashflows, etc. are shown.

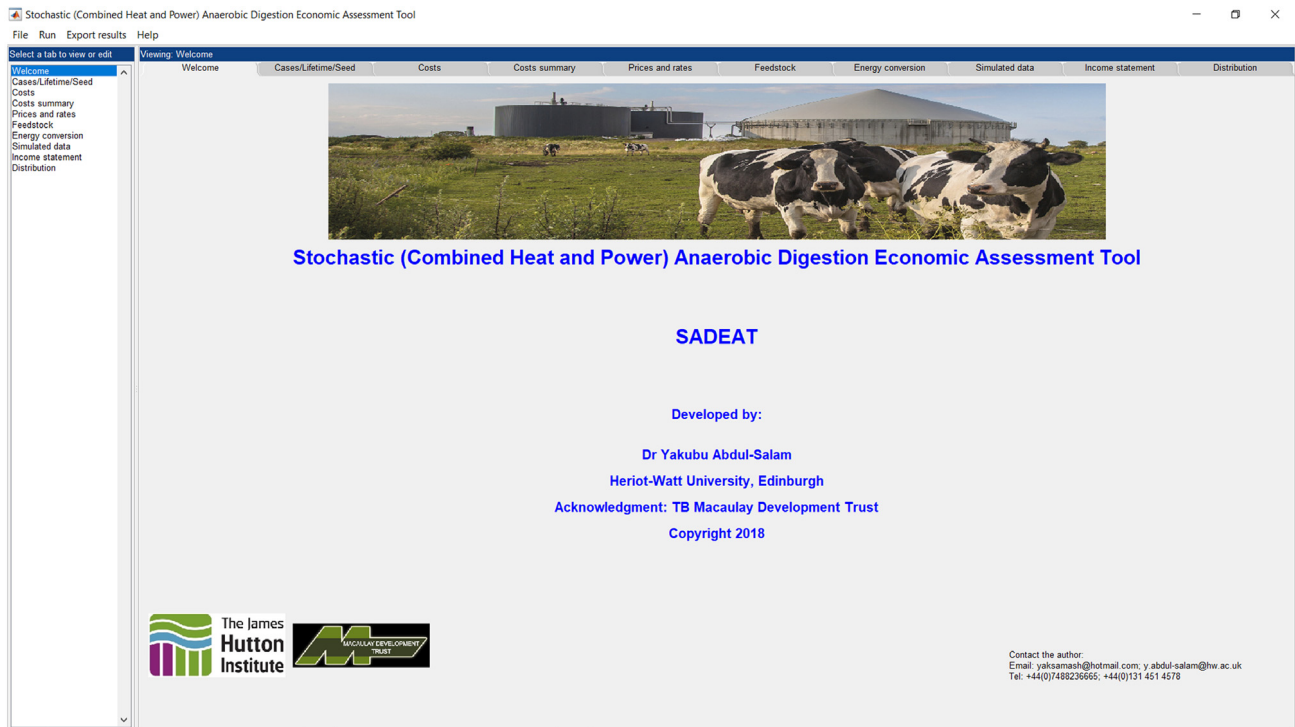


Fig. 1. SADEAT interface.

Building and infrastructure capital costs, £		Machinery capital costs, £		Overhead costs, £	
AD Digester	155000.00	CIP generator	256000.00	Initial year overhead cost	
Separator	0.00	Cables and pipes	0.00	Labour	40000.00
Feedstock and other storage	330000.00	Heat exchanger	0.00	Regular and casual	20000.00
Digestate storage	0.00	Biogas scrubber	0.00	Management	20000.00
Grid connection	26000.00	Fencing	0.00	General overheads	
Start/Backup boiler	0.00	Depackaging	0.00	General insurance	10000.00
Water connection	10000.00	Cleaning technology	0.00	Transport	10000.00
Groundworks	30000.00	Degritter	0.00	Water	0.00
Reception building	0.00	Odour management	0.00	Assurances	0.00
Silage clamp	0.00	Front end loader	0.00	Professional fees	10000.00
Weighbridge	0.00	Pumps	0.00	Testing fees	300.00
Grease trap	0.00	Shredder	0.00	Office and telephone	0.00
Wheel wash	0.00	Pasteuriser	0.00	Miscellaneous	40000.00
Roadways	30000.00	Other	80000.00	Land and building	
District heating system	0.00	Grant assistance	0.00	Rent	0.00
Mixing pit	0.00	Total machinery cost	336000.00	Total	150300.00
Noise reduction	0.00				
Project development	38000.00				
Professional costs	0.00				
Other	1000.00				
Grant assistance	0.00				
Total building cost	620000.00				

Fig. 2. SADEAT interface for tab 'Costs', showing example inputs.

### 3.1.9. Income statement

This is a result tab (see Fig. 4). The tab allows the user a graphical view of summaries of annual income statements across all simulated cases. Mean, minimum, maximum and 95% confidence intervals for annual revenues, costs, cashflows, etc. over all simulated cases are graphically shown.

### 3.1.10. Distribution

This is a result tab. The tab allows the user to view the distribution of any of the four decision support criteria simulated. There are also notes to summarise the information shown in the distribution (see Fig. 5).



Fig. 3. SADEAT interface for tab 'Feedstock', showing example inputs.

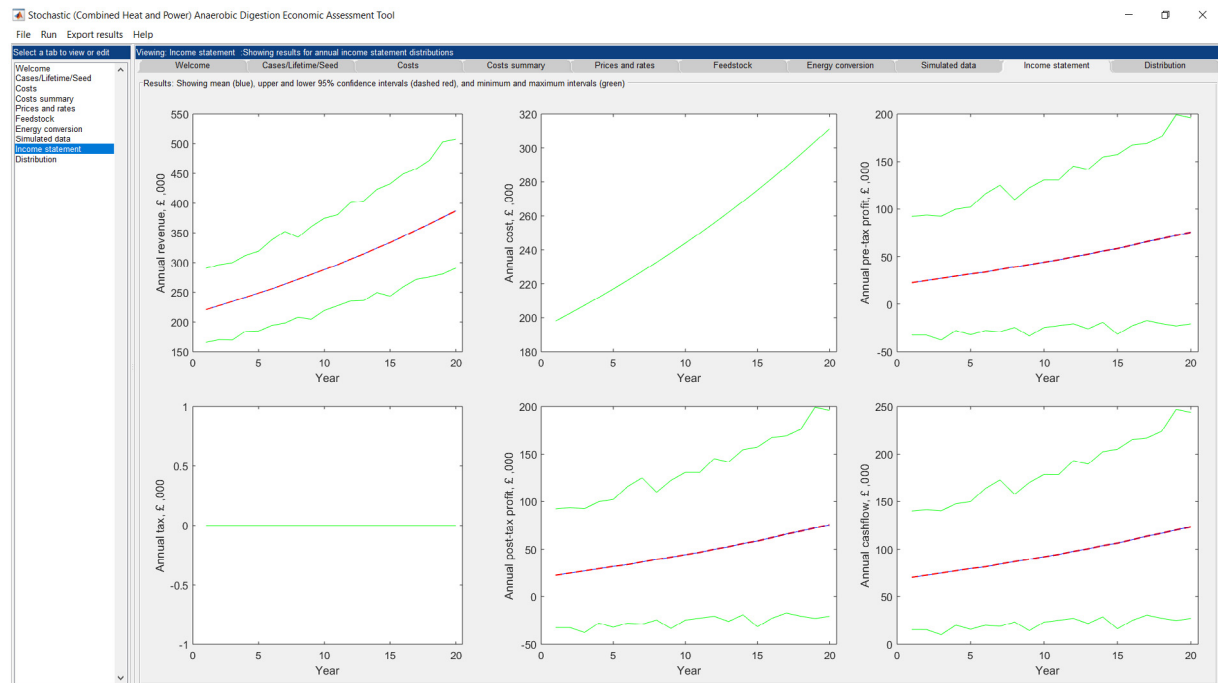


Fig. 4. SADEAT interface for tab 'Income statement', showing example results.

### 3.2. Error controls

There are copious prompts in SADEAT to warn the user of errors in inputs. The main prompts are occasioned by the following events or conditions;

#### 3.2.1. Blank, non-numbers and negative numbers

SADEAT does not allow blank, non-number or negative user inputs. If the user occasions any such scenario, SADEAT triggers a message to warn the user that such inputs are not allowed and that the previous value in the input box had been restored.

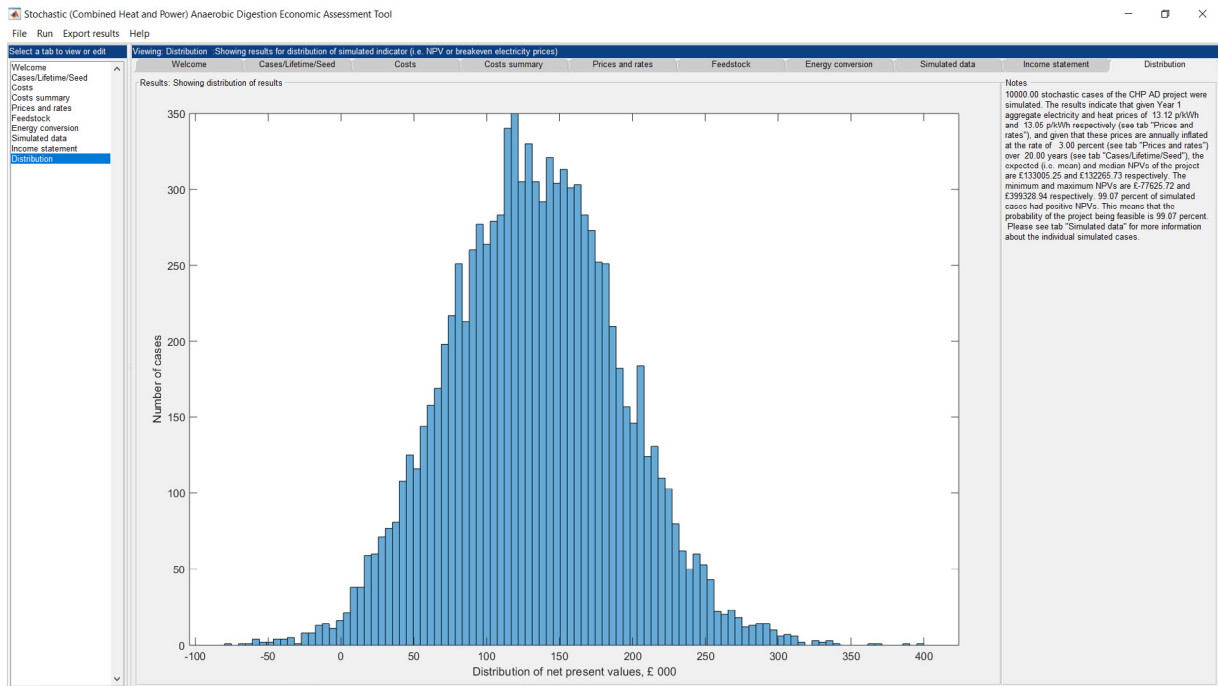


Fig. 5. SADEAT interface for tab 'Distribution', showing example results.

### 3.2.2. Parameters requiring input of integer numbers only

A number of parameters require input of integer numbers only. These include the project lifetime (years), number of AD cases to simulate, seed number for controlling stochastic behaviour, the building and machinery depreciation durations (years) and the debt repayment term (years). If the user inputs a non-integer number for these parameters, the number inputted would be rounded up to the nearest integer. A warning message is also triggered to inform the user of this correction.

### 3.2.3. Parameters with limits on the range of numbers

Some parameters have restrictions on the range of numbers they intake. Some of these restrictions are natural. For example percentages are restricted to 0–100% only. Others are in recognition of AD regulation. For example, project lifetime has been restricted to a maximum of 20 years since FIT and RHI payments are typically made for up to 20 years only. Some restrictions are arbitrary. For example the maximum number of cases the user can simulate is 10,000. This limit is only imposed to reduce computational burden on SADEAT.

### 3.2.4. Parameters with logical controls

Some parameters have logical controls on the values they can intake. For example, the building and machinery depreciation periods (years) and the debt repayment term (years) cannot be greater than the project lifetime (years). Also for the distributions, maximum values of project parameters cannot be less than modal or minimum values; modal values cannot be less than minimum values. If a user input occasions a violation of these restrictions, SADEAT triggers a message to warn the user that a violation has occurred and that the previous value in the box had been restored.

### 3.2.5. Non-generation of electricity and/or heat

A scenario may arise such that the user entries imply zero energy generation for all simulated cases (e.g. zero feedstock amounts). If such a scenario arises, SADEAT does not calculate

breakeven prices as this would be mathematically spurious and logically incoherent. Please see the SADEAT user guide for a further discussion of this scenario.

## 4. Illustrating the software

To demonstrate use of SADEAT for AD economic analysis, we implement the software for an example AD project as shown in Table 1. For robustness checks, we also implement the example project using an existing deterministic tool offered by the NN-FCC [10]. Column 1 of Table 1 lists the various input tabs in SADEAT, column 2 shows the generic variables in each tab and column 3 shows inputs for our example project as applied to SADEAT and the NNFFCC model.

Fig. 6 shows the result of SADEAT for our example AD project in Table 1. Distributions for the 4 indicators of AD economic feasibility are shown.

The results in Fig. 6 show that the expected NPV, MIRR, and breakeven electricity and heat prices are £31,249, 7.35%, 12.95 p/kWh and 12.84 p/kWh respectively. 59.61% of the 10,000 simulated cases had a positive NPV, meaning that there is a 59.61% chance of project success. On the basis of the NPV alone, the AD project exemplified in Table 1 has potential and may be undertaken with the expectation that it would return 7.35% over its 20 year lifetime. Given a combined heat price of 13.05 p/kWh (i.e. 6.94 p/kWh RHI plus 6.11 p/kWh export price of heat), the project needs a minimum combined electricity price of 12.95 p/kWh to breakeven over its lifetime. Likewise given a combined electricity price of 13.12 p/kWh (i.e. 8.21 p/kWh FIT plus 4.91 p/kWh export electricity price), the project needs a minimum combined heat price of 12.84 p/kWh to breakeven over its lifetime. SADEAT provides textual summaries of all results.

The NNFFCC model result gives the NPV of the project as -£267,000, meaning the project is economically infeasible and should not be undertaken. This contrasting result clearly illustrates

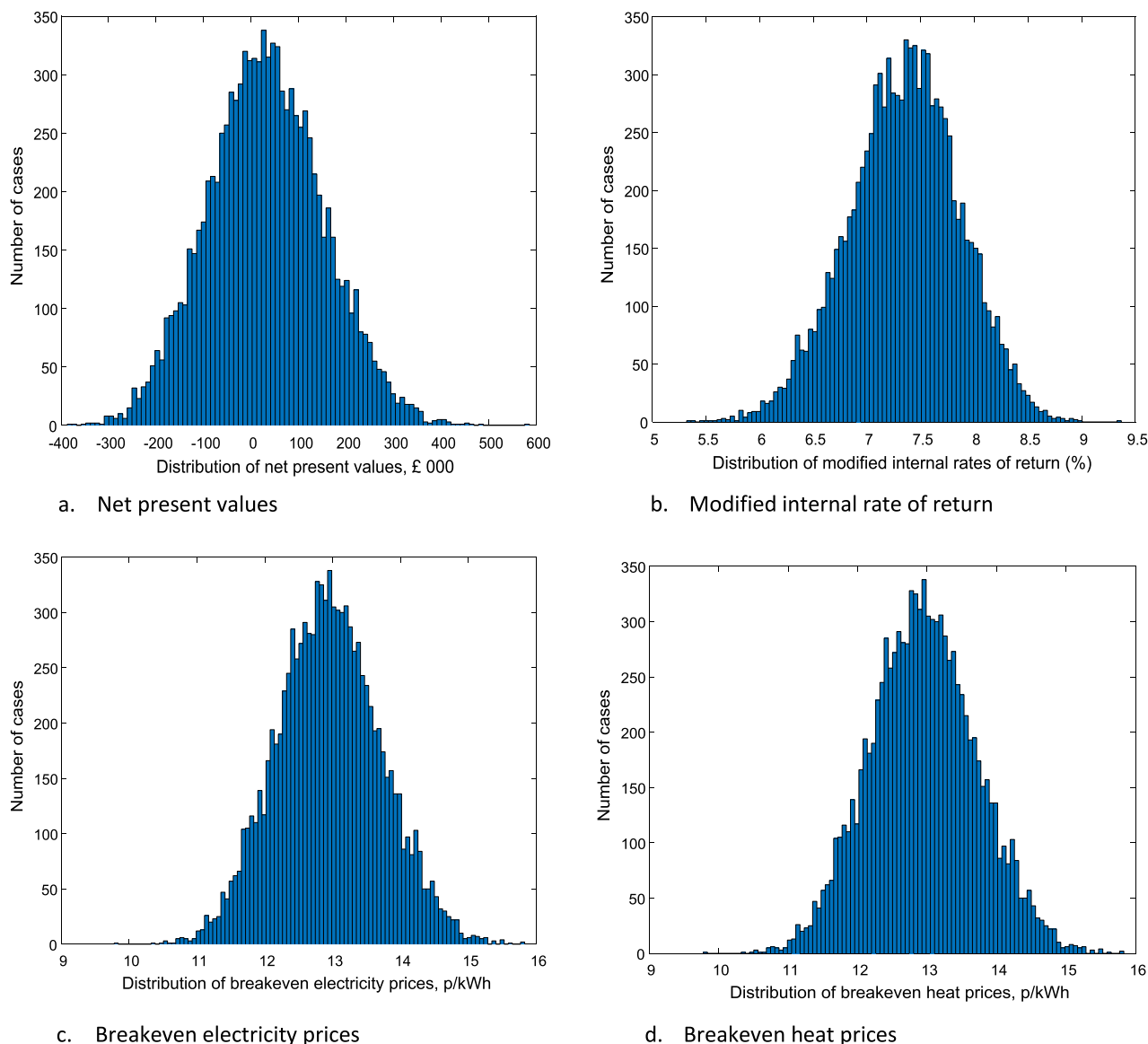


Fig. 6. SADEAT results for example AD project in Table 1.

the advantage of the stochastic methodology in SADEAT rather than the deterministic methodology in the NNFCC model.

Implementing SADEAT means the project is likely to be undertaken, conditional on the risk preference of the investor who assesses that the expected NPV is actually positive (i.e. £31,249) with a 59.61% of being realised.

## 5. Conclusions

This paper introduced a freely accessible stochastic anaerobic digestion economic assessment tool (SADEAT) to aid private firms, farmers and scientists seeking to robustly explore the potential of investments in AD projects; and policy makers seeking to explore policy options for the industry. The tool provides a clean break from the tools adopting deterministic approaches; and also provides an advanced user friendly interface that is different from the simple spreadsheet tools that are currently available. SADEAT has a number of limitations. First, it does not take into account the effects of income from digestate and greenhouse gas credits.

Second, although the economic indicators modelled in the present version of SADEAT are the most commonly used in the AD industry, other potentially useful indicators of AD economics (e.g. cost-benefit ratios, payback periods) are not included. Third, SADEAT does not take into account the spatial dimensions of AD economics. The author will seek to address a number of these limitations in future extensions of SADEAT.

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**Table 1**

Example AD project for implementation in SADEAT software.

Tab	Variable	Inputs (SADEAT)	Inputs (NNFCC model)
Welcome	–		
Cases/Lifetime/Seed			
	Project lifetime (years)	20.00	20.00
	Number of cases to simulate	10,000	–
	Seed (for reproducibility of results)	12,345	–
Costs			
	Total building cost (£)	500,000.00	500,000.00
	Total machinery cost (£)	800,000.00	800,000.00
	Total initial year overhead costs (£)	150,000.00	150,000.00
Costs summary			
	Building depreciation period (years)	20.00	20.00
	Machinery depreciation period (years)	20.00	20.00
	Percentage of debt (%)	10.00	10.00
	Debt repayment term (years)	10.00	10.00
Prices and rates			
	Feed in tariff for electricity (p/kWh)	8.21	8.21
	Export tariff for electricity (p/kWh)	4.91	4.91
	Renewable heat incentive tariff for heat (p/kWh)	6.94	6.94
	Export tariff for heat (p/kWh)	6.11	6.11
	Debt interest rate (%)	6.50	6.50
	Inflation rate (%)	3.00	3.00
	Cashflow discount rate (%)	6.00	6.00
	Tax rate (%)	0.00	0.00
	MIRR finance rate (%)	6.50	–
	MIRR reinvestment rate (%)	9.00	–
Feedstock			
	Feed 1 (tonnes)	[3000.00, 3500.00, 4000.00] <sup>a</sup>	3500.00
	Yield for feed 1 (tonnes/m3)	[60.00, 90.00, 120.00] <sup>a</sup>	90.00
	Feed 2 (tonnes)	[800.00, 1000.00, 1200.00] <sup>a</sup>	1000.00
	Yield for feed 2 (tonnes/m3)	[170.00, 195.00, 220.00] <sup>a</sup>	195
Energy conversion			
	Energy in methane (kWh/m3)	[11.10, 11.20, 11.30] <sup>a</sup>	11.20
	Amount of methane in biogas (%)	[55.00, 60.00, 80.00] <sup>a</sup>	60.00
	Plant electricity efficiency (%)	[33.00, 39.00, 45.00] <sup>a</sup>	39.00
	Plant heat efficiency (%)	[38.00, 43.00, 48.00] <sup>a</sup>	43.00
	Overall plant inefficiency (%)	[5.00, 10.00, 15.00] <sup>a</sup>	10.00
	Parasitic electricity load (%)	[6.00, 8.00, 10.00] <sup>a</sup>	8.00
	Parasitic heat load (%)	[20.00, 30.00, 40.00] <sup>a</sup>	30.00
	Downtime (%)	[10.00, 15.00, 20.00] <sup>a</sup>	15.00

<sup>a</sup> Triangular distribution inputs [Minimum, Modal, Maximum].

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